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14. ABSTRACT

The geometrical anisotropy and bi-anisotropy of a split ring and post type metamaterial is studied by free space microwave measurements in a frequency band near 13.5 GHz where it exhibits negative index of refraction. The orientation of the linearly polarized incident wave determines whether the refracted response is negative or positive. Measurements of cross polarization through the prism are 50% of the co-polarization. The insertion loss through the material of 3.36 dB/cm at 13.5 GHz, where the index n = -1, is therefore composed of both scattering and absorptive losses.

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Measured Polarization Response of Negative Index Metamaterial

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Abstract

Free space microwave measurements are reported of a split ring and post type metamaterial that exhibits negative index of refraction in a frequency band near 13.5 GHz. Varying azimuthal angles and magnitudes are achieved by changing the polarization of the transmitter and receiver relative to each other and to the anisotropic material. The amplitude of the cross-polarized transmission has been measured at 50 % of the co-polarization level. This polarization conversion is a significant loss mechanism.

1. INTRODUCTION

The theoretical possibility of alternate, propagating solutions to Maxwell's equations by media with simultaneously negative electric permittivity and magnetic permeability was first proposed by Veselago [1] in 1967. He predicted several effects unique to such media, including negative index of refraction. In the usual positive refraction between two media, the refracted ray crosses to the opposite side of the optical normal axis from the incident ray. Negative refraction occurs at an interface between positive and negative index media. The refracted ray is bent to the same side of the normal as the incident ray. Negative index media have also been referred to as left-handed, double negative and backward wave media. Veselago's work assumed the medium was homogeneous, isotropic and continuous. The first experimental demonstration of negative index of refraction [2] used a metamaterial consisting of a periodic array of metallic inclusions made up by split ring resonators (SRR) and long narrow posts. This material was not isotropic, and only effectively homogenous or continuous due to its tenth wavelength cell size, but it displayed negative refraction nonetheless. Because of the material's anisotropy, this first demonstration of negative refraction required a linearly polarized electromagnetic field propagating along an axis, similar to the optical axis of a crystal. The anisotropy of negative index media may be particularly complex. The SRR-post type metamaterial we have measured, which is similar to those reported in the literature, can exhibit positive or negative refraction at the same frequency. The negative region has also shown bi-anisotropic coupling between electric and magnetic response, which was proposed by Marques et al. [3].

The practical application of negative index media will require greater understanding and improvement of the concomitant losses. Our initial effort to differentiate absorption and scattering losses led us to look at polarization effects. The aim of this paper is to present our results demonstrating the anisotropic and bi-anisotropic behavior of a negative index metamaterial and to discuss the scattering losses.

2. FABRICATION

The negative index metamaterial combines two different structures. Long, thin metallic posts simulate electrical plasma producing negative permittivity. Split ring resonators provide the magnetic plasma characteristic producing negative permeability in a frequency band near their self-resonance [4]. The posts and rings are etched front-to-back in 1-oz copper on 0.25 mm thick Rogers' 5880 circuit board, which has permittivity 2.2 at 10 GHz. The unit cell used in this work is shown in Fig. 1. The outer ring is 2.7 mm on a side. The line width of the rings is 0.25 mm, the space between rings is 0.30 mm and the gap in each ring is 0.51 mm across. The post on the back is 0.76 mm wide. The unit cell is stepped in an array with 3.71 mm spacing center to center. The posts are joined top to bottom across adjoining cells to form continuous posts 250 mm long.

To measure refraction a wedge shaped prism is used, shown as if viewed from above in Fig. 2. The prism is formed from strips of etched substrates cut into varying widths. The strips are spaced with 3.2 mm layers of Emerson and Cuming Eccosorb™ PP2 foam, which is essentially transparent to microwaves. The orientation of the boards in the prism is vertical, i.e. out of the page of Fig. 2, and perpendicular to the incident face of the prism. The prism increases in thickness from 6 to 16 cells by one cell for every five strips across the width. This produces a wedge apex angle of 12^0. Four rectangular prisms, or slabs, were similarly constructed. The slabs were 1, 3, 6 or 16

cells thickness. The width of each prism was 20 cm and the height 25 cm. To hold its shape each prism was wrapped in Top Flight MonoKote, a thin self-adhesive plastic with very low microwave loss, which is typically used to cover model airplanes.

3. MEASUREMENTS

All measurements in this report were performed in free space in an anechoic chamber, with matched square transmit and receive horns measuring 20 cm on a side. Each horn has a 3dB width of 14°. The transmit horn is mounted 3.73 m from the prism. The prisms were placed in a baffle with an aperture 20 cm by 25 cm. The receive horn is mounted on a rotating arm 2.58m from the prism allowing us to measure the angular distribution of the transmitted signal. The horns are connected to a HP-8530A transceiver to measure the amplitude and phase. For these apertures and the frequencies used near 14 GHz, the transmit and receive distance are both beyond R1, the reactive near field distance, given by

$$R1 = 0.62(D^3/\lambda)^{1/2} \quad (1)$$

where D is the maximum linear dimension of the source aperture and λ is the free space wavelength.

3.1. Verification of negative refraction

The initial experiment was a refraction measurement using the wedge prism to confirm negative index. Because of the anisotropy of the medium, a linearly polarized TEM wave with the electric field vector oriented parallel to the posts and the magnetic field vector normal to the plane of the SRRs in the structure is required to excite negative refraction. This polarization is shown in Fig. 2 as the upper vector triplet. The incident beam is normal to the entrance face of the prism and continues into the metamaterial without refracting. The beam strikes the second face at an angle equal to the prism apex angle of 12°, and is refracted there. The refracted angles are assigned negative or positive values according to whether the beam is bent to the same or opposite side of the normal as the incident beam, as labeled in Fig. 2. The index of refraction, *n*, for the metamaterial is calculated by applying Snell's Law,

$$n\sin(\alpha) = n_0 \sin(\theta_r) \quad (2)$$

where $n_0 = 1$, α is 12° and θ_r is the measured exit angle in air.

3.2. Frequency response

The refracted angle of the wedge prism was measured for different frequencies. The calculated index as a function of frequency is shown in Fig. 3. The frequency region for which the index is negative is necessarily limited and highly dispersive. Our metamaterial is unusual in exhibiting adjacent frequency bands of negative and positive index. The rate of change of the index in the negative region of Fig. 3 fits a linear slope of 1.16, approximately an order of magnitude greater than the positive index slope of 0.16.

Transmission through the metamaterial slabs was measured to show the frequency response. Recall the slabs were made 1, 3, 6 and 16 cells thickness. The results are shown in Fig. 4. Comparing Figs. 3 and 4, note that index n= -1 for the wedge occurs at 13.5 GHz and lies along the leading edge of the pass band of the slabs. At this frequency, the insertion loss varies from -3.5 to -16 dB depending on slab thickness. The insertion loss at this frequency as averaged from the measurements is 3.36 dB/cm. The maximum transmission in the negative index band however does not occur at n=-1, but at 14.1 GHz where n = -0.38. The average loss through the slabs is 1.06 dB/cm at this frequency, significantly lower than for n = -1.

All transmission losses are either absorptive or scattered. To investigate the scattered loss, we want to distinguish the anisotropy due to the geometry of the structures and the bi-anisotropic nature of the negative index response.

3.3. Rotated polarization

The anisotropic prisms which we fabricated are described in the literature as an indefinite medium [5]. The permittivity and the permeability tensors include both positive and negative values, so the x and y components may equal 1 while the z component may equal -1. The effect of this anisotropy can be demonstrated with the wedge prism and a TEM wave polarized as shown by the lower vector triplet of Fig. 2. Both the transmitter and receiver polarization are rotated by 90° from our initial arrangement. This orientation, with the electric field perpendicular to the posts and the magnetic field parallel to the plane of the rings, minimizes the interaction of both fields with the structures. The direction of propagation was maintained normal to the entrance face of the wedge prism. The exit angle was measured at +12° from the normal, meaning the index of the prism for this polarization is equal to +1. The results of angle sweeps at 13.5 GHz for both polarizations are

shown in Fig. 5. The response is similar to previous measurements for a unit cell with two posts [6].

3.4. Cross polarization

The cross polarization of the wedge prism was measured with the transmitter vertical and the receiver horizontal. As Fig. 6 shows, at 13.5 GHz the horizontal receiver detected a signal peak at the same angle (-12 from the normal) and almost 50% the magnitude of the co-polar case. The measurement indicates that polarization rotation is a significant scattering loss mechanism which has been previously neglected. The existence of the cross polarized field indicates that the SRRs themselves have an electromagnetic asymmetry. We speculate that the cause of the large cross polarization may be that the resultant field vector radiated by the SRR is not parallel to the planes of the posts. This may be related to what Marques [3] describes as the bi-anisotropy of the SRR, which has orthogonal electric and magnetic dipole moments and a coupled electric and magnetic dipole moment. Since energy is not absorbed but rotated into another polarization, we define this as scattering loss.

It should be noted that wave guide or guided wave chambers, which are frequently used to characterize negative index media, have restricted propagation modes limited by their boundary conditions. If the cross polarization we observe in free space does not correspond to an allowed guide mode, the signal would be attenuated. The associated loss would be mistaken for absorption, not scattering, if measured in a guided wave system.

4. CONCLUSIONS

In this investigation we have demonstrated the geometrical anisotropy and bi-anisotropy of the metamaterial by studying its response to linearly polarized fields. It has been shown that the polarization of the incident wave determines whether the refracted response is negative or positive. Measurements of cross polarization through the prism of 50% of the co-polarization value have shown that the scattered loss for this medium is significant and can not be ignored. The insertion loss through the material of 3.36 dB/cm at 13.5 GHz, where the index n = -1, is therefore composed of both scattering and absorptive losses. The polarization measurements of this SRR-post metamaterial indicate that both the anisotropic and bi-anisotropic behavior require further investigation.

5. ACKNOWLEDGEMENT

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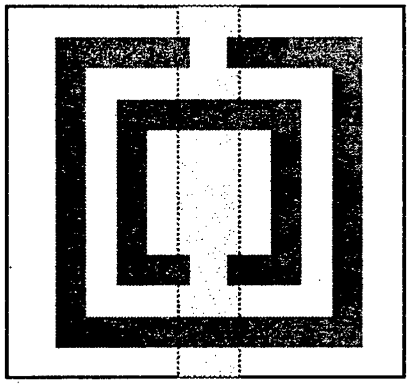

Fig. 1. Unit cell

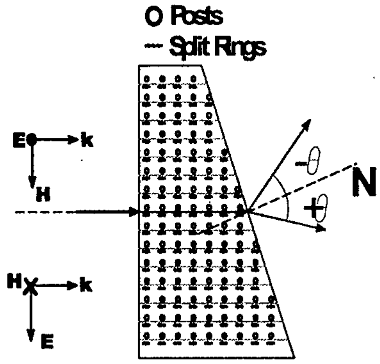

Fig. 2. The measurement set-up.

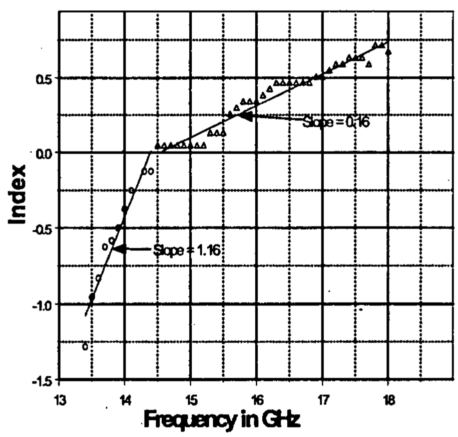

Fig. 3. Dispersion for SRR-P prism

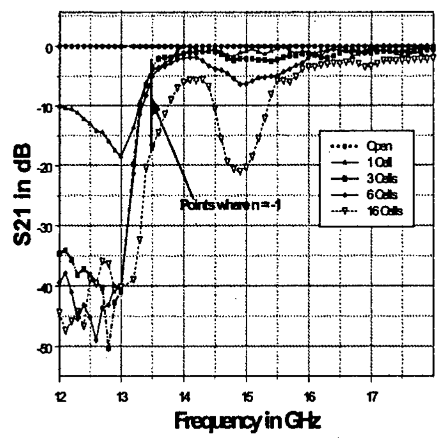

Fig. 4 Frequency response for SRR-P Slabs

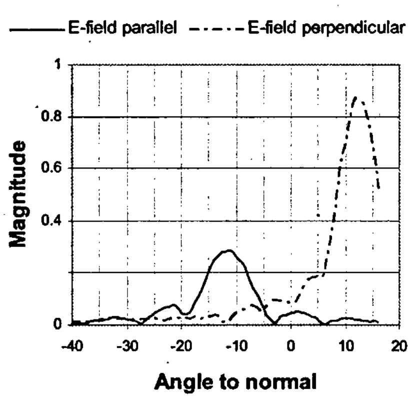

Fig. 5. Positive and negative anisotropy

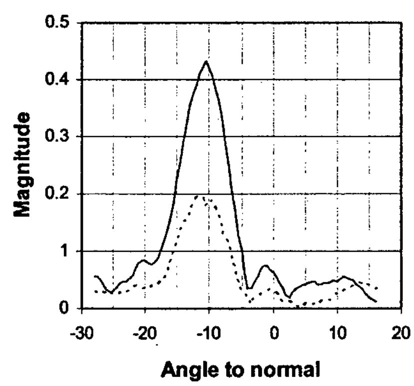

Fig. 6. Co- and cross- polarization through wedge